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Title: Wave Generation and Wave-Particle Interaction Using Space-Based, RF, Linear Electron Accelerators

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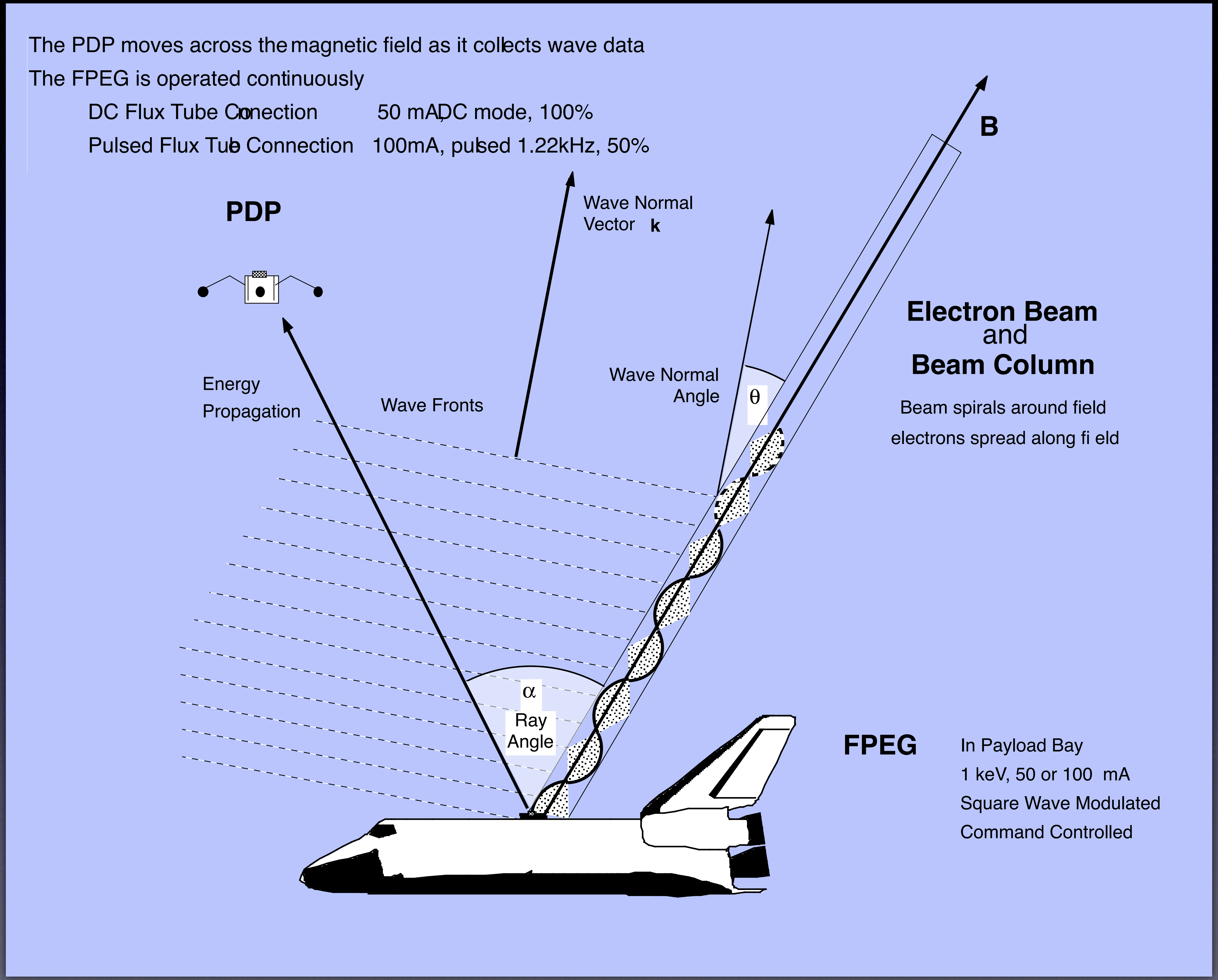
Wave Generation and Wave-Particle Interaction Using Space-Based, RF, Linear Electron Accelerators

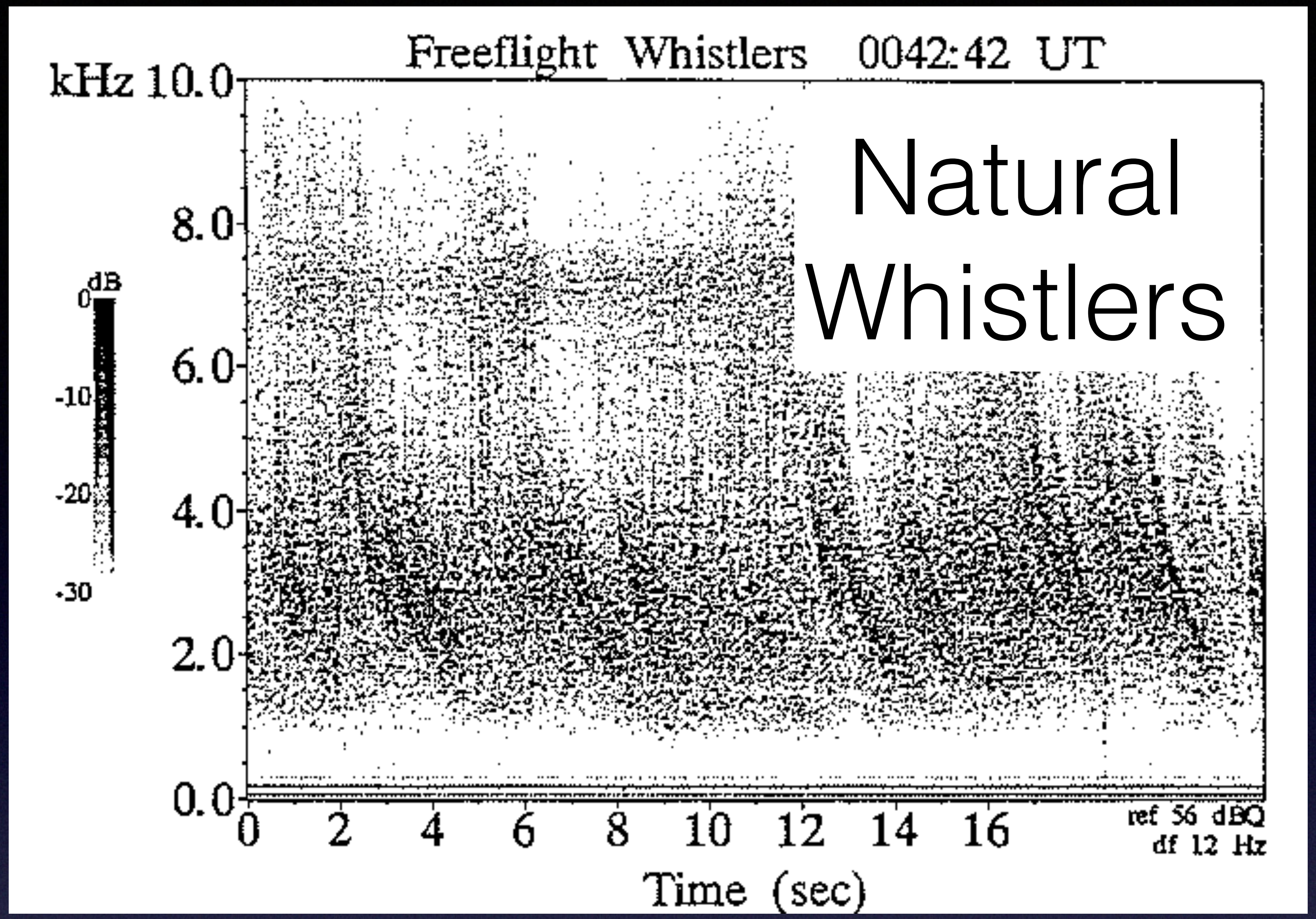
Geoffrey Reeves

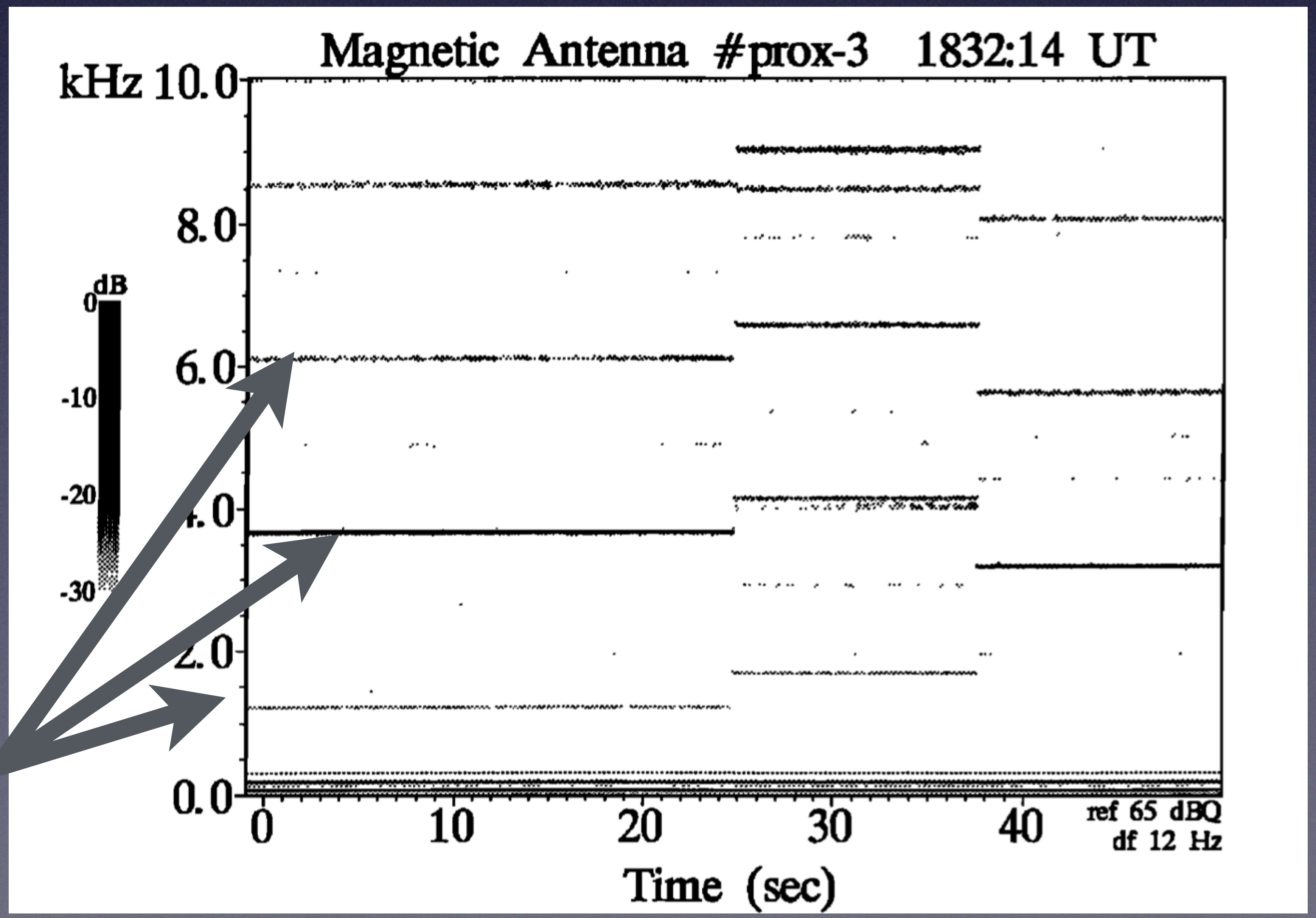
and the Beam PIE and RBR-ACES Teams

- Active experiments in wave-particle interactions using electron beams date back to the 1980s but went through a prolonged period of inactivity
- Van Allen Probes and other missions have vastly increased our understanding of wave particle interactions and their importance
- Technologies for beam generation, wave receivers, and particle detectors have seen huge advances in capability
- There’s an opportunity for a new generation of active experiments to produce fundamental discoveries under controlled conditions not available in the natural environment

STS-3 and Spacelab 2







Stimulated Emissions & harmonics

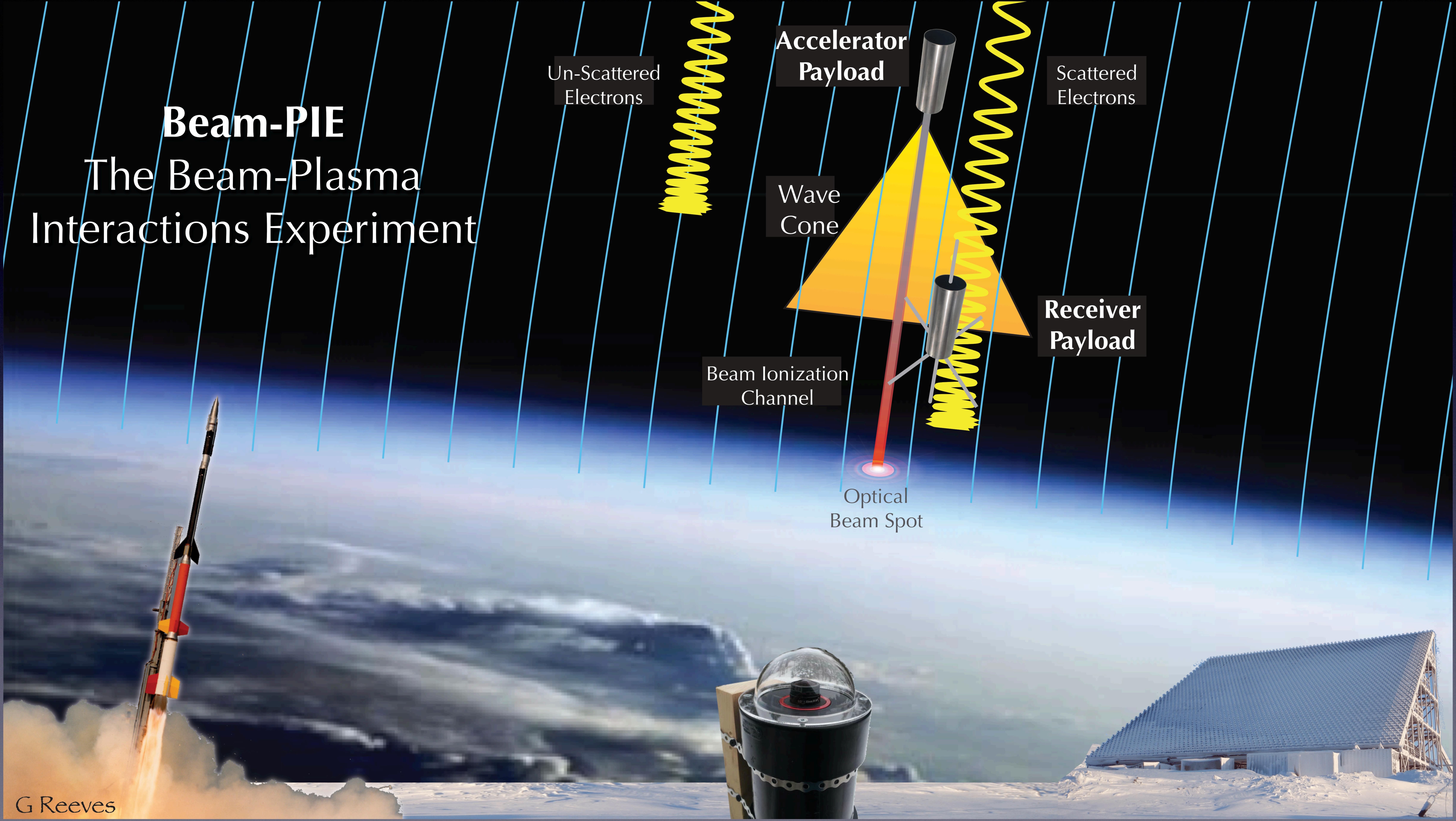
Reeves et al., 1988, 1990

Shuttle and rocket experiments confirmed:

- waves are stimulated by coherent Cherenkov emission
- observed waves are consistent with whistler mode
- spatial coherence and harmonic structure showed the beam propagated a long way without major instabilities (contrary to simulations)
- dependence on pitch angle, frequency, duty cycle, etc. were qualitatively consistent with theory [Harker and Banks, 1986]

They could not:

- vary the energy of the beam
- measure waveforms for wave normal angle, ellipticity, planarity, etc.
- resolve spectral width of the emissions (important for pitch angle diffusion and non-linear scattering calculations)
- measure the effect of the waves on particles
- measure frequencies above ω_{ce} where X-mode waves are predicted


Beam-PIE
The Beam-Plasma
Interactions Experiment
Un-Scattered
Electrons
Accelerator
Payload
Scattered
Electrons
Wave
Cone
Receiver
Payload
Beam Ionization
Channel
Optical
Beam Spot
G Reeves

Beam PIE Basics

- Joint LANL and GSFC collaboration
- We use a pulsed electron beam to generate waves using various frequencies, duty cycles, and energies
- A second payload measures waves, particles, and background plasma parameters (B, density, temperature)
- Measurements are capable of <u>quantitative</u> comparison against linear theory and simulations
- Non-linear effects can be resolved
- Nominal Launch is March 1, 2022

Beam PIE Components

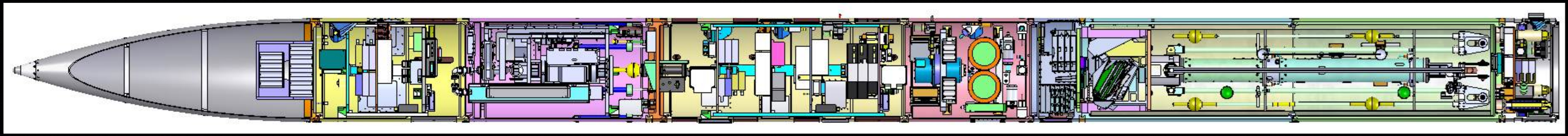
- Accelerator Payload: no measurements, spacecraft charging mitigated by maximizing surface area (e.g. nosecone)

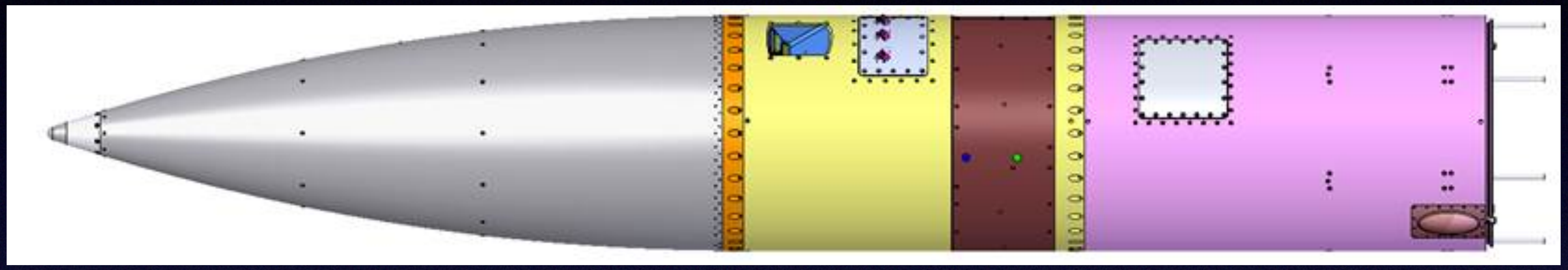
- Wave Receiver Payload: full E and B waveform capture at VLF frequencies, 1D E component at HF frequencies

- Effect of Waves on Particles: two detectors to look for electron pitch angle scattering

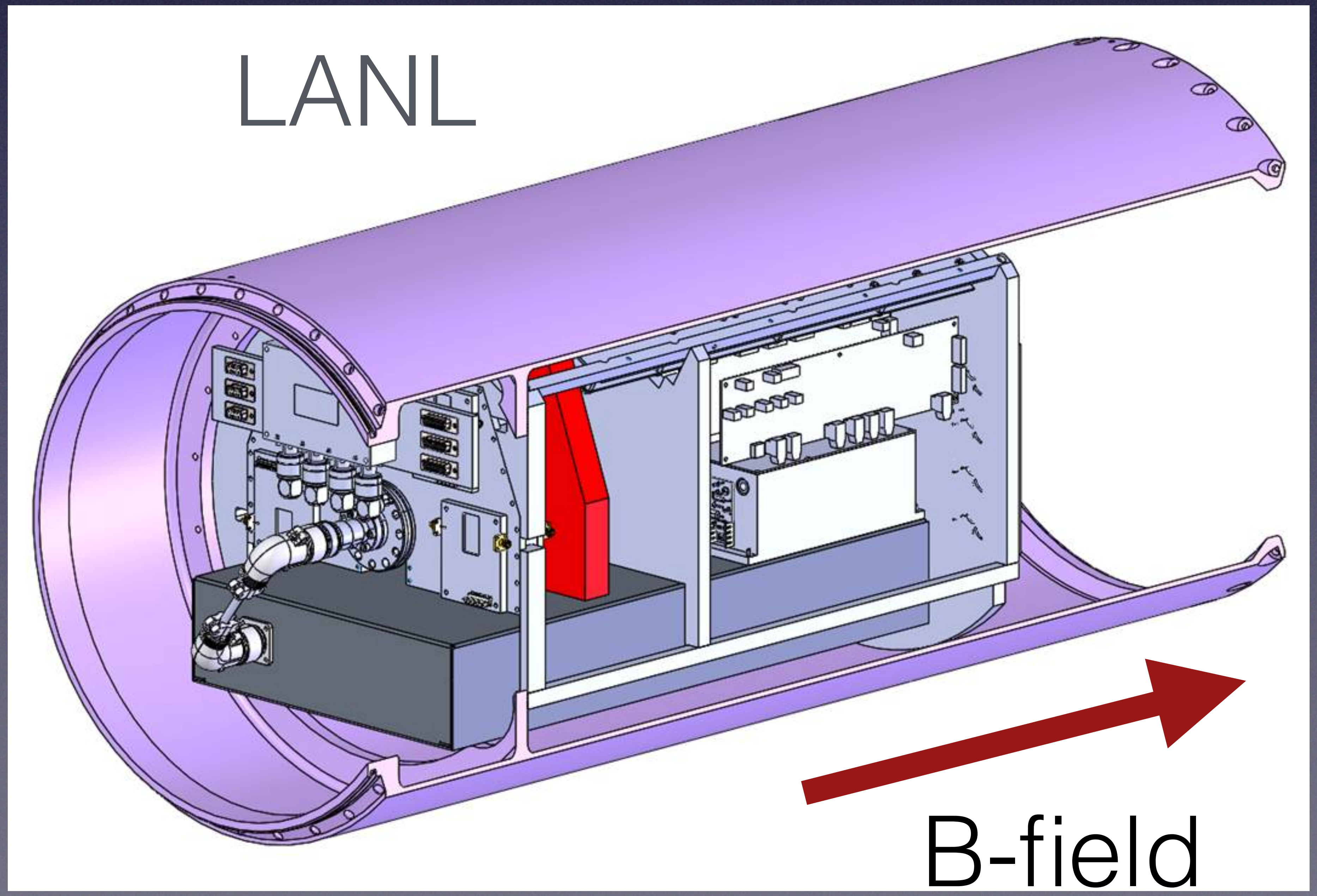
- Ground Segment: will measure optical emissions from beam interaction with the atmosphere to assess beam propagation

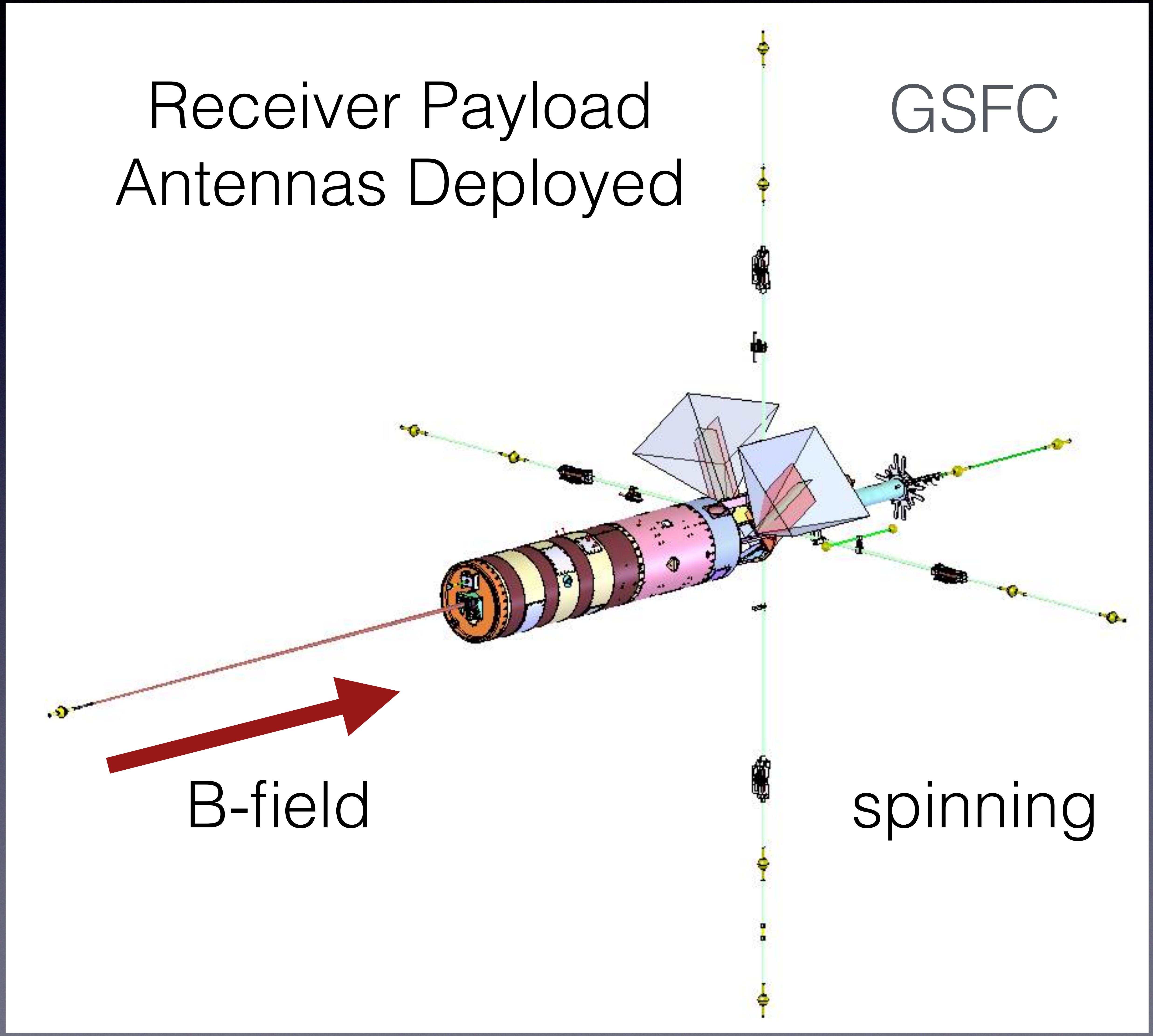
- Theory & Simulation of: Accelerator, Beam Propagation, Wave Generation, & pitch angle scattering



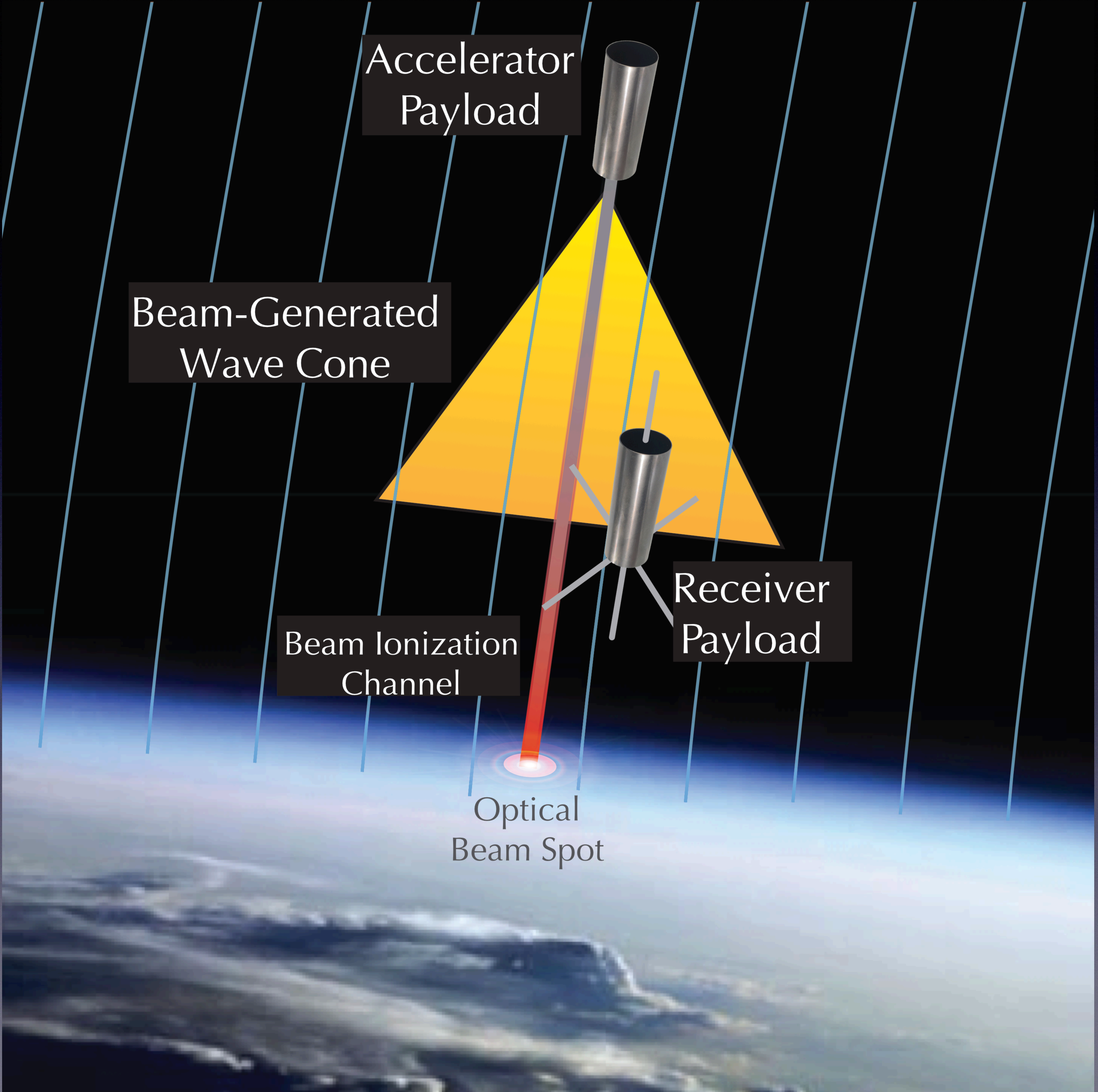


Accelerator with Nosecone attached to minimize charging





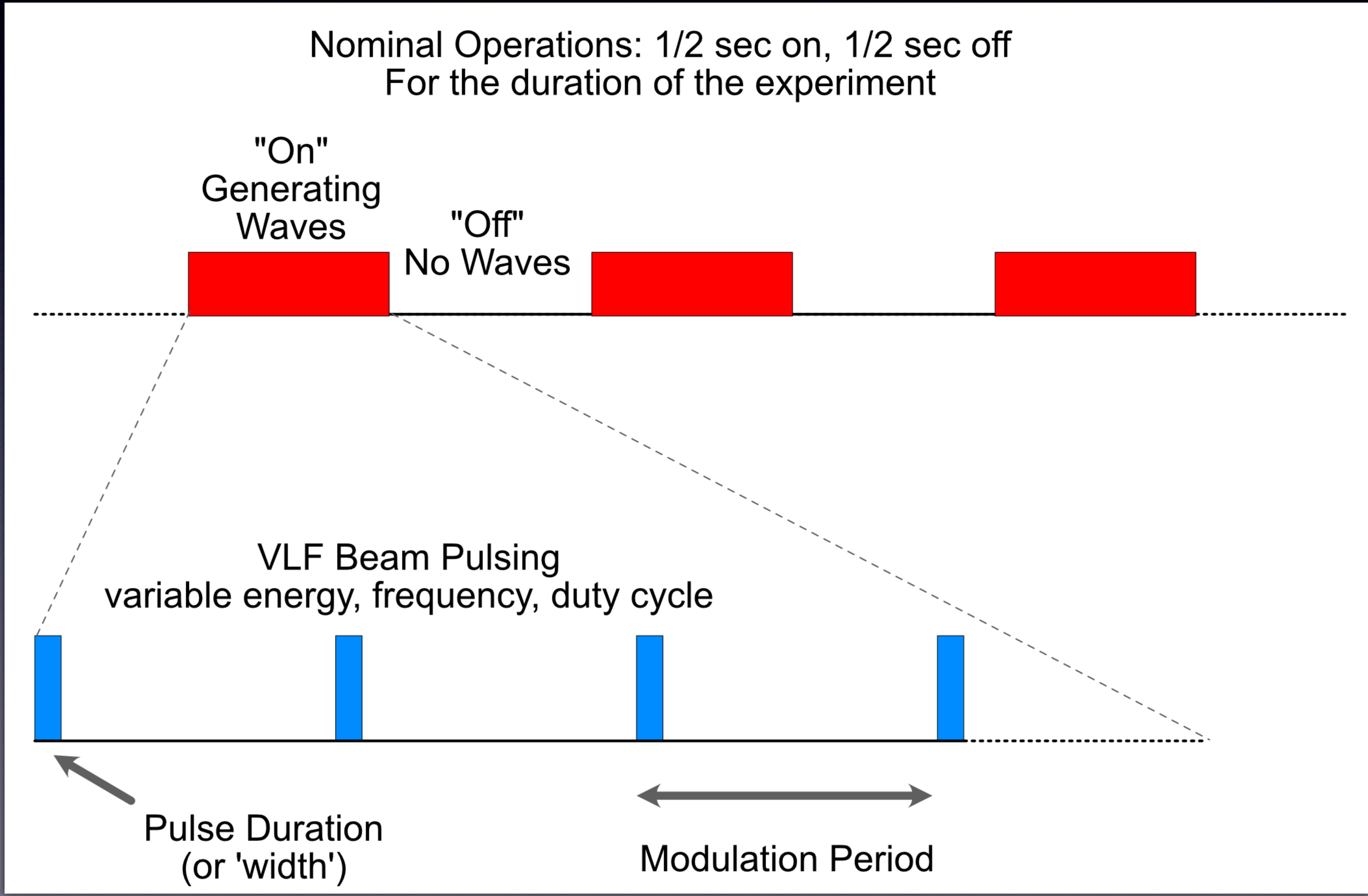

Accelerator
&
Electronics
Electron
Beam
70°
90°
Plasma
Spectrometers
3-Axis Electric
Field Probes
ACS
Combined
Electronics
& Burst
Memory
Langmuir Probe
3-Axis
Search Coils
Vector
Mag.
New: 1D HF Receiver



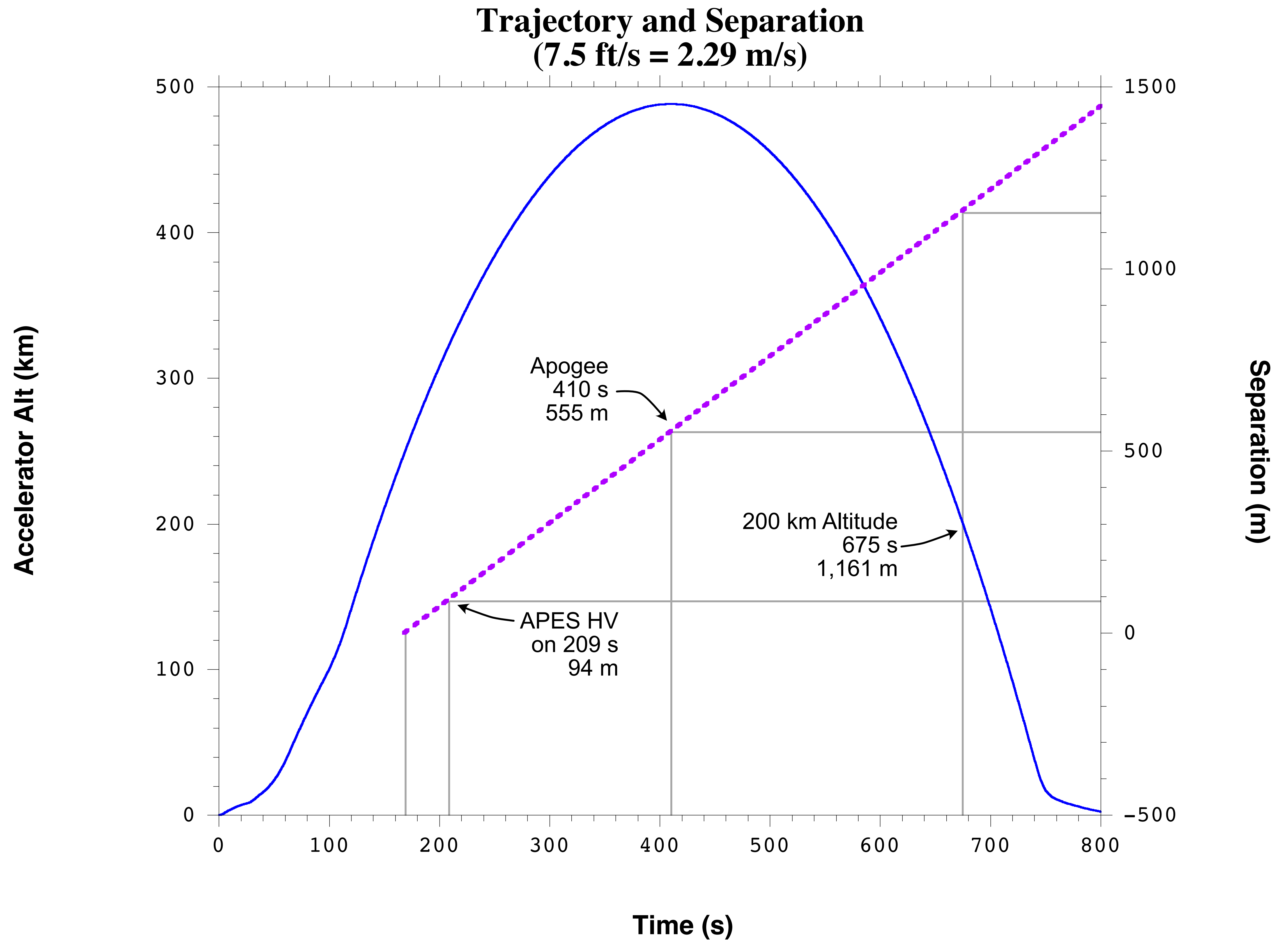
- Accelerator and receiver aligned along B
- Gradually separate
- We are not trying to measure the beam with the receiver
- We measure the waves in a cone around B

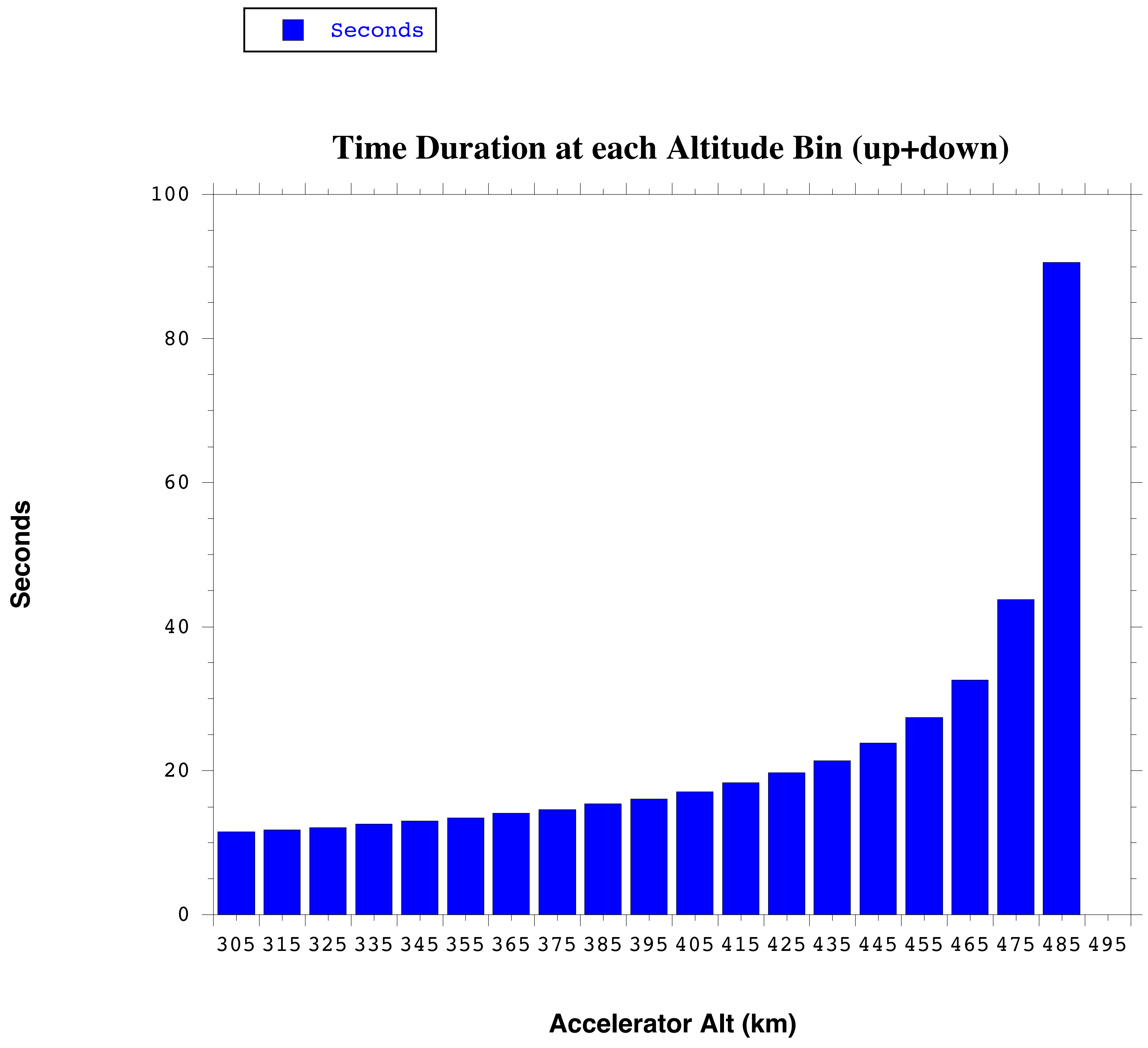
The beam pulsing scheme lets us

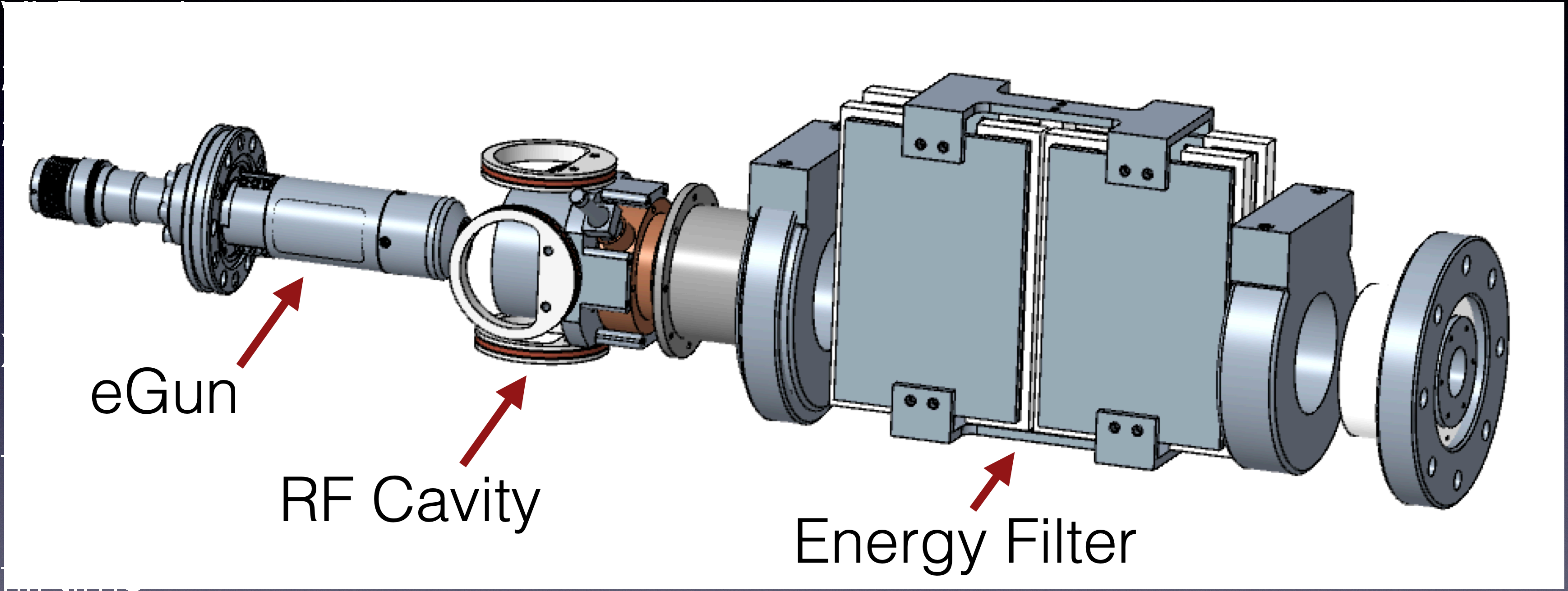
- vary energy, frequency, and duty cycle independently
- compare wave & particle measurements when the beam is on with background measurements when the beam is off



Each ½ second (energy, frequency, duty cycle) sequence will be repeated at different separations and background plasma conditions

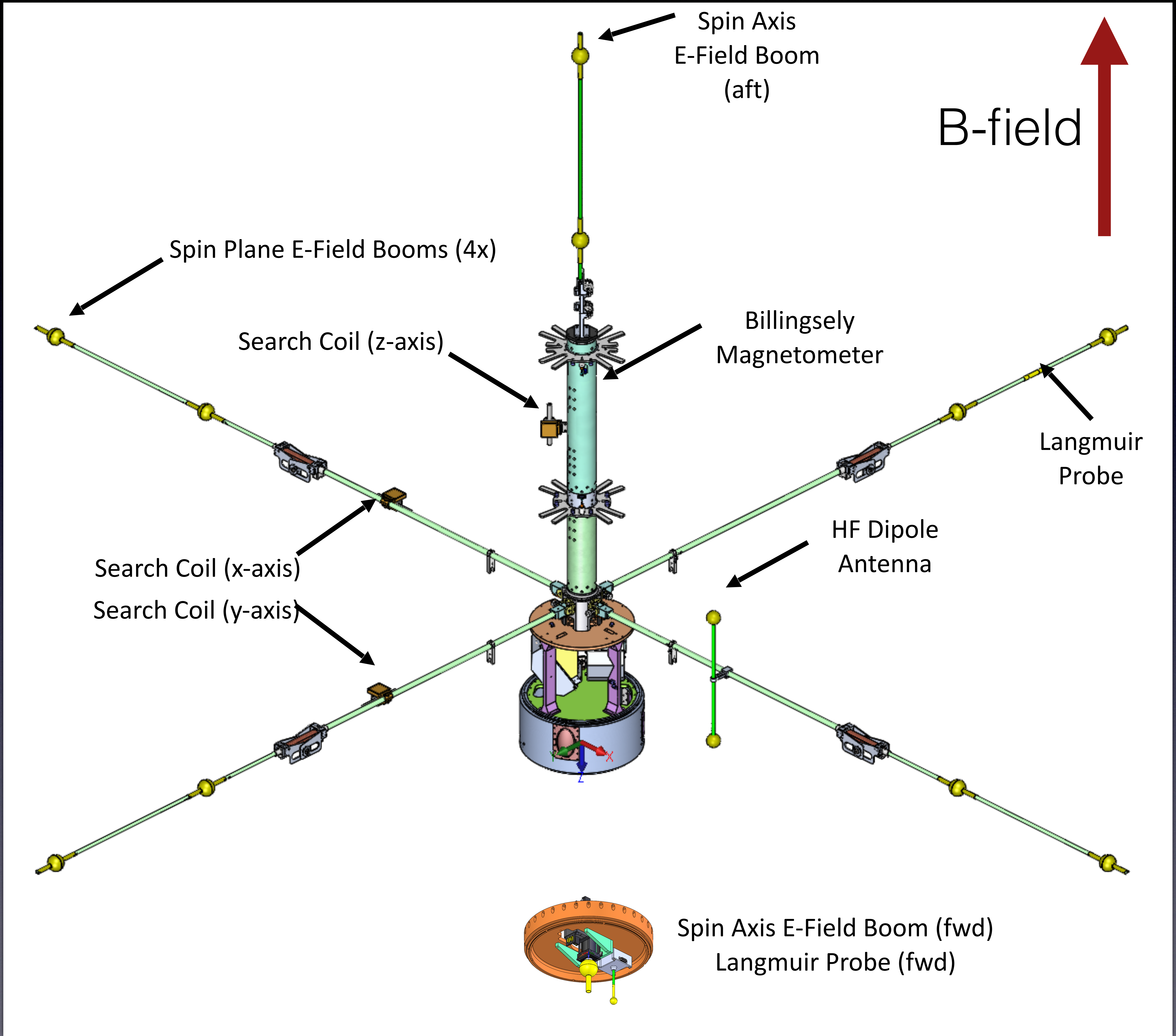


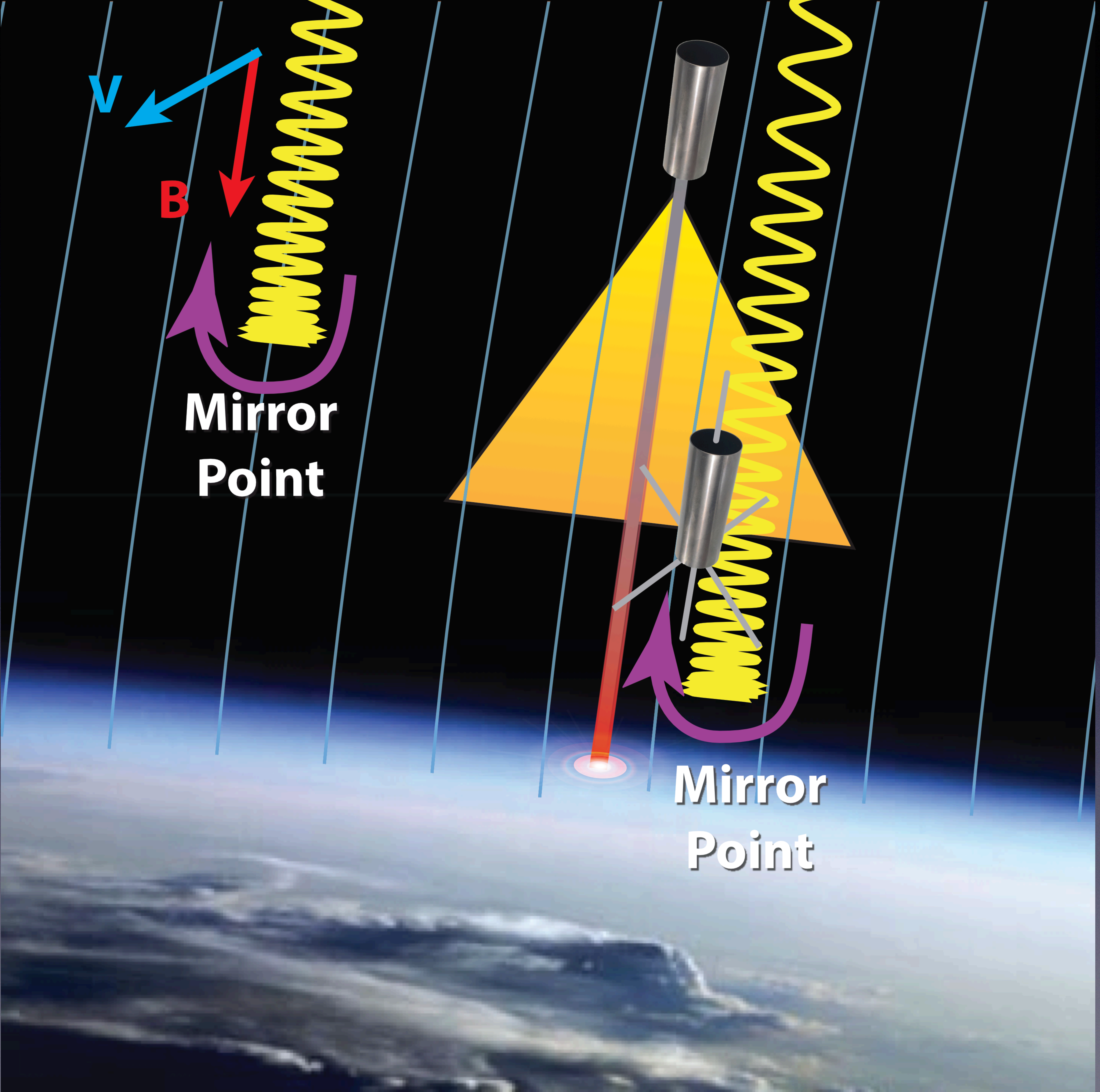



eGun
RF Cavity
Energy Filter

GSFC/Pfaff, Farrell

- E-field booms
  - Dual-hinge fiberglass
  - Fold-out axial boom
  - Stacer boom (axial)
- Langmuir Probes
- Search Coil sensors
- Billingsley Magnetometer
- Fields Electronics Box



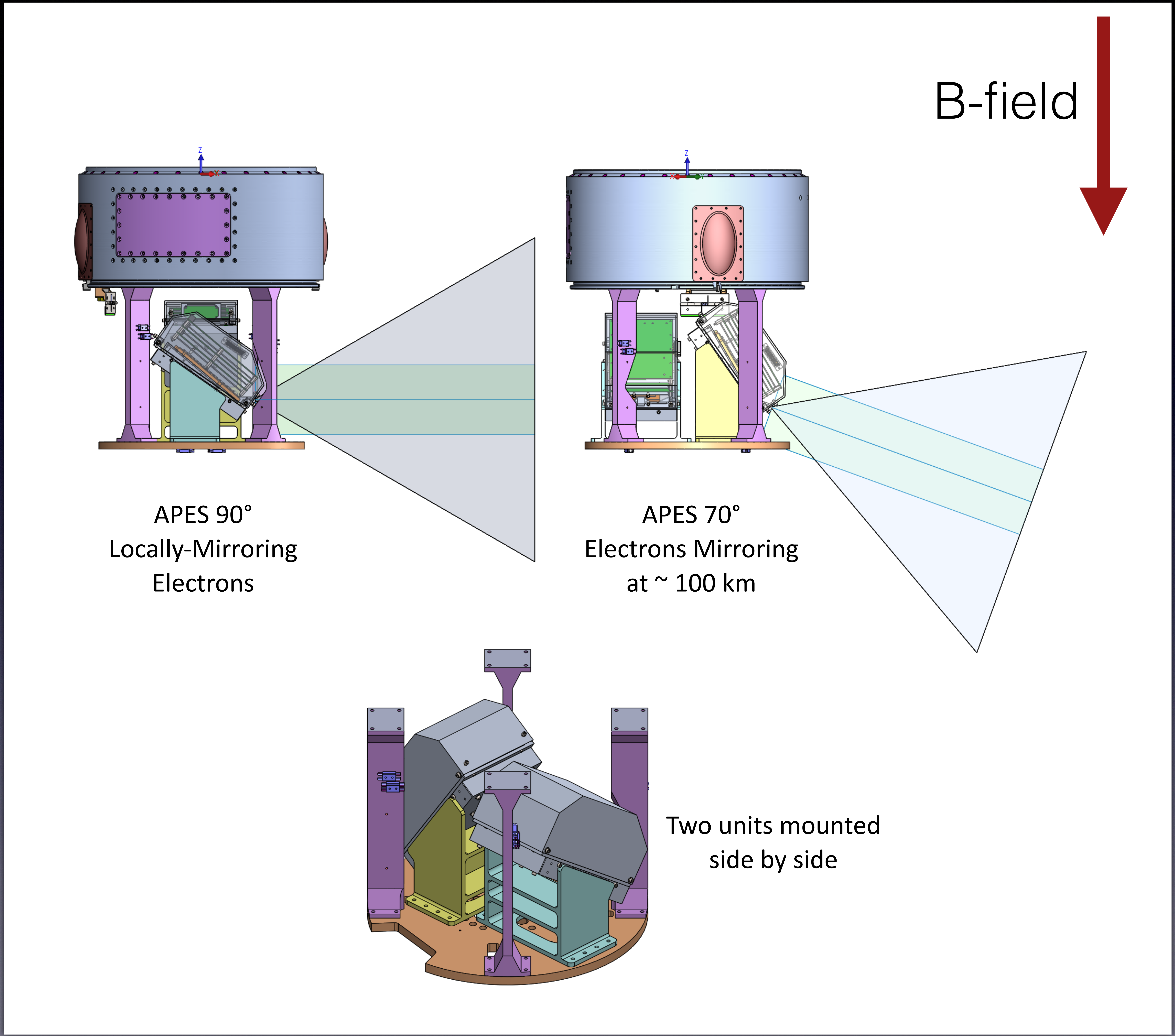


- At 300-500 km most ambient electrons (10s keV) mirror above the receiver
- We look for scattering by comparing the flux of particles mirroring locally (90°) and below the receiver (70°)
- Compare flux ratio with beam ON vs beam OFF

GSFC/Samara

-- APES electron detector

-- HF Analog Experiment



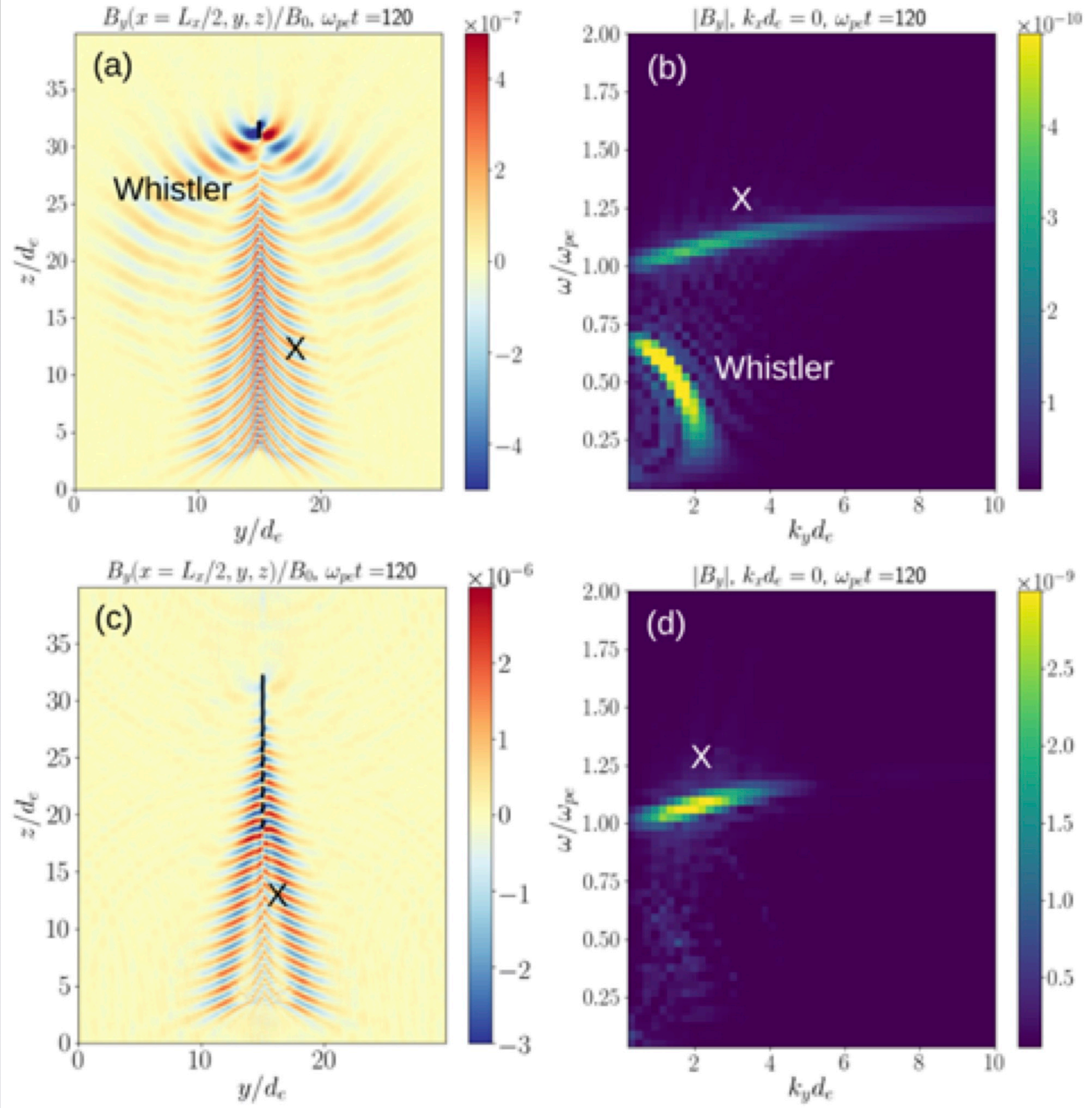
Parameters that determine wave characteristics

- Beam Energy
- Beam Frequency
- Beam Duty Cycle
- Ambient Plasma conditions (B, density, temperature)

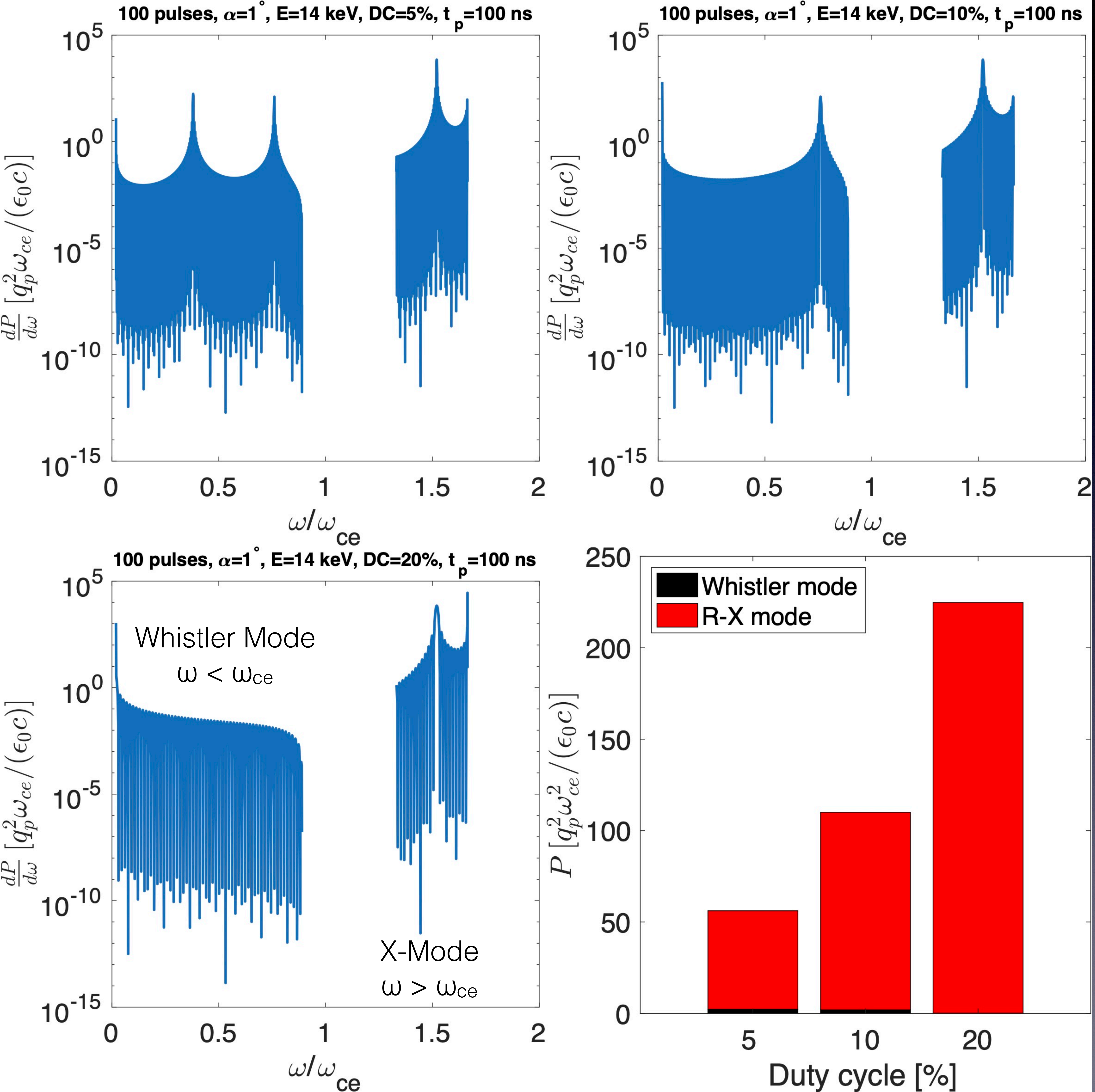
Pulse width in microseconds						Period in microseconds	Frequency in Hertz
1	2.5%	2	5.0%	4	10.0%	40	25,000
1	2.0%	2	4.0%	5	10.0%	50	20,000
3	3.0%	5	5.0%	10	10.0%	100	10,000
12	2.4%	25	5.0%	50	10.0%	500	2,000

Can repeat all of these every 12 seconds ≈ 25 complete repeated sequences

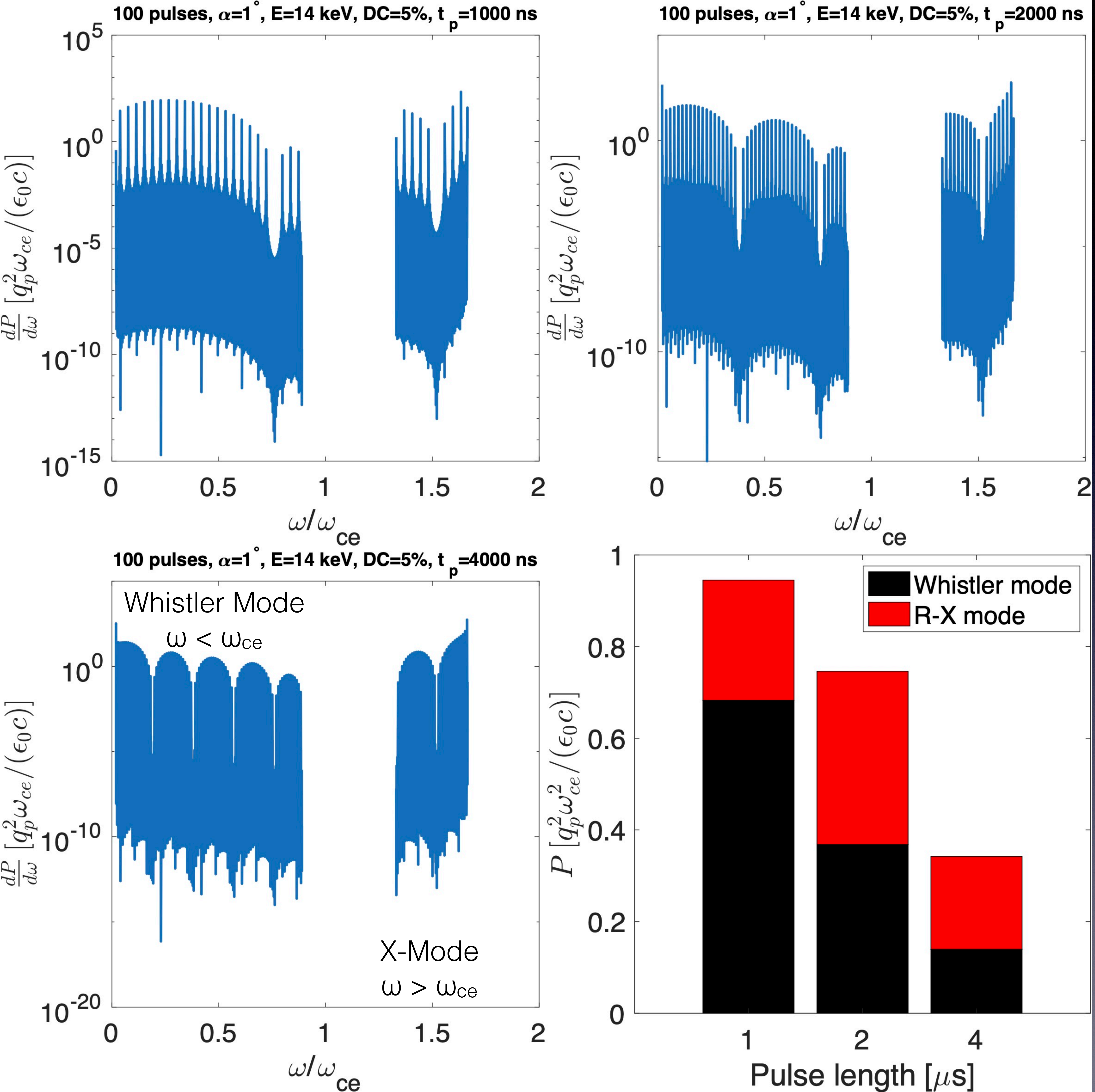
- Prediction of Wave Characteristics as a function of beam pulsing parameters.
- One new tool is Spectral Plasma Solver (SPS) methods. [Delzanno et al., 2015]
- SPS is like PIC but solves the equations in the spectral domain
- Well suited for wave-particle interactions because of inherently low numerical noise



- SPS simulations show both X-mode and Whistler-mode waves will be generated
- Different pulsing schemes will determine Whistler & X mode spectra
- Whistler mode waves have a broad wave cone
- X mode waves may only be detected at small cross-field separations



- Dependence on Duty Cycle
- 5% to 20% duty cycle
- 14 keV, 100 ns duration
- Blue curves show power spectrum with harmonics at N times pulsing frequency
- Whistler mode at $\omega < \omega_{ce}$
- X Mode at $\omega > \omega_{ce}$



- Dependence on Pulse Duration
- 1 s to 4 s pulse duration
- 14 keV, 5% duty cycle
- Blue curves show power spectrum with harmonics at N times pulsing frequency
- Short pulse durations (higher frequency modulation) produce strong X Mode response
- Minimum duration limited by RF cavity filling time (not yet known)

“Conclusions”

- If everything works the results should be really cool
- The methodology allows very sensitive and quantitative tests for quasi-linear theory - both for wave generation by particles and particle scattering by waves
- We can and will measure waves generated by non-linear processes
- Narrow-band waves are more likely to produce non-linear pitch angle scattering which will also be tested
- Electron beams are currently being investigated for use in Radiation Belt Remediation [Reeves et al., 2018, 2020]